# Assessing the stiffness of the Achille's tendon using laser vibrometry

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# Assessing the Stiffness of the Achilles tendon using Laser Doppler Vibrometry

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## Abstract

There were approximately 232,000 Achilles tendon sports injuries in the United States for individuals six and over. The reasons for injuries are weak blood supply to the Achilles tendon and bowstring effect due to ankle pronation. Prior to tear of the Achilles tendon, the tendon may become thinner and not as stiff as normal. Achilles tendon surgery involves either a large incision in the back of the lower leg or several smaller incisions in the same area. Currently, doctors examine Achilles tendon injuries by using Magnetic Resonance Imaging (MRI) scan which can be expensive and time consuming. On the other hand, vibration-based methods can assess the stiffness of structures (such as beam, cables or human tendons) by measuring the propagation velocity of induced vibrations, in which faster propagation velocities indicate stiffer material or tissues. To determine the optima placement and positioning of the LDV and shaker along the Achilles tendon as well as optima frequency band for the shaker excitation to maximize the signal-to-noise ratio of the measured vibrations. The initial procedure included a vibration shaker to vibrate the Achilles tendon and a single Laser Doppler Vibrometer (LDV) to measure the guided vibrations propagating along the Achilles tendons a few cm away from the shaker. Data were recorded using Labview and analyzed with MATLAB. The data were collected multiple times to see the robustness of the setup. The vibration amplitude and frequency are extracted from the Doppler shift of the reflected laser beam frequency due to the motion of the surface. The target velocity component will be extracted as the output of LDV. At each collected data point the time domain of the delay of the response is shown. Repeated date collection at same position of the laser beam was assessed to see the robustness of the protocol. Table 1 shows the time delay of the response at the same point and their standard deviation. Our goal is to reduce the standard deviation between similar data collection sets. It can be concluded that assessing the stiffness of the Achilles tendon using Laser Doppler Vibrometry can ensure the safety and efficiency of diagnosing Achilles tendon injuries.

## Introduction

Researchers have investigated the biomechanics of Achilles tendon for a long time because the Achilles tendon, being both the largest and strongest tendon in the body, is the most frequently injured tendon in the entire body. Achilles tendon surgery involves either a large incision in the back of the lower leg or several smaller incisions in the same area. This is why it is important to assess the Achilles tendon stiffness that is obtained from a combination of motion analysis. There are approximately 260,000 athletes suffering from substantial Achilles tendon injuries every year[1]. Since this number is only limited to athletes, it can be assumed that the total number of Achilles tendon injuries is greater. The specific mechanism of Achilles tendon injuries has not been defined but it is predicted that a sudden increase of a repetitive activity involving the Achilles tendon puts too much stress on the tendon too quickly, leading to micro-injury of the tendon fibers. The ongoing stress on the tendon inhibits the body to repair the injured tissue and the local reduction in stiffness of the Achilles tendon can be observed[2].

Various non-invasive detection techniques have been investigated to ease the process of repairing the Achilles tendon. A combination of B-mode and power Doppler ultrasonography (US) is generally the most common imaging examination in patients with Achilles tendinopathy because of its wide availability and low cost[2]. Magnetic resonance (MR) imaging is also a widely used examination technique. Even though the diagnostic accuracy of the US and MR still remains controversial, both methods are only showing whether there is a rupture in the Achilles tendon. It is hard to determine if there are changes in stiffness and strength in the Achilles tendon. The mechanical properties of the Achilles tendon should be quantified for better diagnosis of the patient's injuries. Vibration-based methods can be used to quantify the mechanical properties of the Achilles tendon. This can be done by measuring the velocity of the propagated mechanical vibrations along the Achilles tendon. The stiffer the Achilles tendon, the faster the velocity of the propagated vibrations would be [3].

The purpose for this research is to investigate the mechanical properties of the Achille's tendon using laser vibrometry. A vibration shaker will be used to propagate the mechanical vibrations along the

Achilles tendon and a single Laser Doppler Vibrometer (LDV) will be used to measure the propagated vibrations. This setup can provide a non-invasive diagnostic technique that applies no force to the Achilles tendon. Collection of the data will be done by LabView program and analyzed by MATLAB program. The current purpose of the study is to achieve the robustness of the experimental settings. The optimal position of the LDV and the placement of shaker along the Achilles tendon are determined as well as optimal frequency band for the shaker excitation are collected using the LDV. Another objective is to determine how the physical exercises that stretch the Achilles tendon prior to the data collection affects the repeatability of the measurements. The repeatability of the data collection will be accessed by comparing the standard deviations of the similar data collection sets.

## Literature review

It was discovered that the Achilles tendon insertional angle is not influenced by ankle subtler joint motion in those with and without enthesitis by three dimensional gait analysis to measure walking speed, rotational joint motion and the moments of the subjects with psoriatic arthritis[1]. The field of assessing mechanical properties of the Achilles tendon relatively new task for many researchers. The objective for the research is to investigate the mechanical properties of the Achille's tendon laser-based elastography using a single scanning laser vibrometer. The technique will be validated using calibrated Laser Doppler Vibrometer. In this paper, current methodologies of assessing mechanical properties of the Achilles tendon will be discussed based on literature reviews.

The study by Castellini demonstrates the new uses on Laser Doppler Vibrometry (LDV) development that are investigated with the innovative solutions regarding to the most recent technological requirements which are not common in the current systems[2]. Several LDV application areas are described and the limitations of actual technologies such as LDV resolution, uncertainty assessment, direction uncertainty, LDV stand-off distance[2]. The possible solutions needed to overcome these limits are anticipated and emerging technologies which are not completely entered the market but could positively answer to the industrial requirement are described[2]. The fact that the Achilles tendon insertional angle was not influenced by ankle subtler joint motion is proven by three dimensional gait analysis to measure walking speed, rotational joint motion and the moments of the subjects with psoriatic arthritis[3]. The current clinical application and analysis are done on disease affecting Achilles tendon. It is necessary to compare how they assess the tendon stiffness and how we are approaching to the problem.

A continuous scanning laser Doppler vibrometry (CSLDV) obtained sweeping a single laser beam along a periodic scan pattern allows measuring surface vibrations at many points simultaneously by demultiplexing the CSLDV signal[3]. This method can be used to measure in a non-contact manner the velocity of low-frequency surface waves on the soft materials in our case, human body tissues. It is effective in measuring the increase in surface wave velocity over the muscles that correlate to the stiffening of the tissues[3]. However, the current experiment strategy in this research sticks to the conventional scanning laser vibrometry techniques that the laser beam is fixed at a single point during each measurement and moves to another point manually prior to the next measurement. This is why this research only focuses on the propagation velocity of mechanical vibrations to estimate the regional stiffness of Achilles tendon and even though we are only considering position of the leg and angle of the joint, the increasing or decreasing strain that affects tendon stiffness generated from adjusting leg on a fixed position should be taken into account for the settings.

The future study using LDV will be dealing with clinical fixation or treatment of Achilles tendon. To do that, it is important to know physiological background of how the LDV measures the muscle stiffness. Patients with musculoskeletal and neuromuscular disorders often have elevated muscle stiffness so that the stiffness of muscle tissues such as Achilles tendon needs to be assessed clinically[3]. Non-invasive ways to estimate the elastic properties of Achilles tendon using a vibration-based method measuring the propagation velocity of mechanical vibrations will be needed. The methods and information provided from the chosen literatures helps to achieve the purpose of this research which is evaluating and investigating the mechanical properties of the Achilles tendon with the non-invasive and safe technique.

## Methods and Materials

*Experimental Setup*

Four LDVs are used to reduce the calibration errors. On the wooden ply, four LDV are lined up with different angles, so that each laser hits the small mirror in different angles. The laser is deflected and directed toward the big mirror located at the corner of the ply, and finally deflected toward the Achilles tendon of the subject. The subject will be sitting on top of the LDVs, or roof of the LDV box (bottom ply and top ply), and Aluminum rod that is attached on a vibration shaker will be applied to the Achilles tendon from the side with 45 degree of angle to propagate the vibration on the tendon. Data will be collected at four different point on the Achilles tendon vertically lined up. Each data point has 1 cm increment starting from the tip of aluminum rod position.

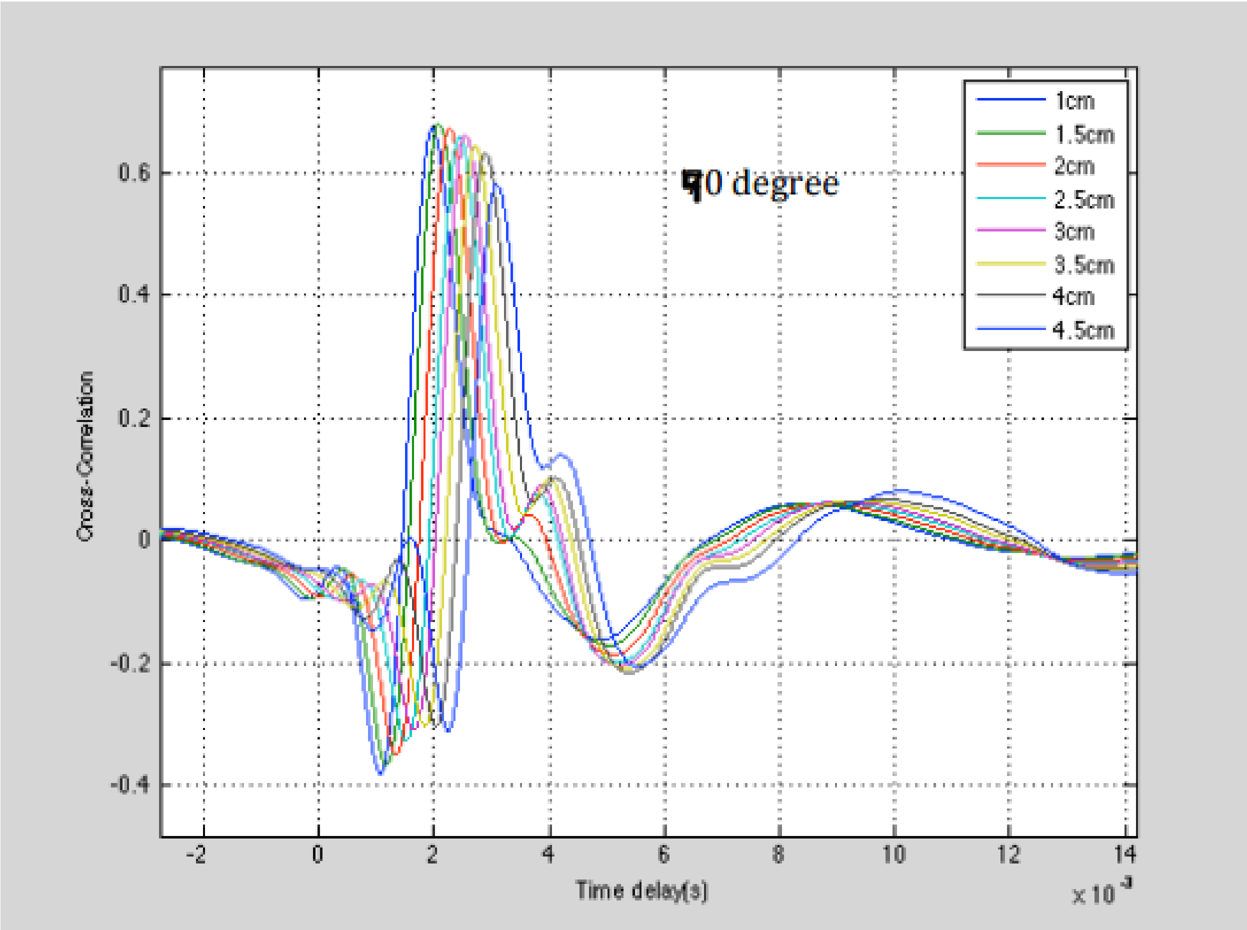
*General procedure*

The initial procedure included a vibration shaker to vibrate the Achilles tendon and a single Laser Doppler Vibrometer (LDV) to measure the guided vibrations propagating along the Achilles tendons a few cm away from the shaker. The LDV has the advantage of being very precise and non-contact thus requiring no cables or skin-mounting. Data were recorded using Labview and analyzed with MATLAB. The data were collected multiple times to see the robustness of the setup. The research setup will then be improved upon once the weaknesses of the setup have been determined. The data collection will repeat until the standard deviation between similar data collection sets is relatively small.

## Results

The vibration amplitude and frequency are extracted from the Doppler shift of the reflected laser beam frequency due to the motion of the surface. The target velocity component was extracted as the output of LDV. At each collected data point the time domain of the delay of the response is shown in Figure 1. Closer the shaker and the laser beam, shorter the delay of the response.

**Figure 1. The Vibration Amplitude and Frequency of Different Data Point at All the Time Point**




*The peaks of the frequency were used to compare the time delays of each data point (1cm to 4.5 cm, with 0.5cm increment). Time delays in second, and the data were collected at 90 degrees of joint angle of the subjects.*

The peak amplitude of each frequency is when the excitation reach back to the laser or responded. It has proven that the time taken to get a response is the fastest if the collection point is the nearest the rod (1cm) and the slowest at the farthest (4cm). As the distance from the collection point and the rod gets bigger, the time delay also becomes larger.

Repeated date collection at same position of the laser beam was assessed to see the robustness of the protocol. Table 1 shows the comparison of time delay of the response at the same point and their standard deviation of the aluminum-excitation-rod and plastic-excitation-rod. The goal is to see if the aluminum rod has delivered the excitation with lower interference, which also means has lower the standard deviation between similar data collection sets. On a single point, times taken to get a response were collected 20 times for each aluminum and plastic rod, and average time and standard deviation were compared (Table 1).

**Table 1. Comparison of Time Delay and Standard Deviation of Aluminum and Plastic Rod**

| | **Average Time Delay** | **Standard Deviation** |
|---|---:|---:|
| **Aluminum** | 5.3655 | 0.30081 |
| **Plastic** | 6.4532 | 0.42502 |

*Aluminum rod was more stable and faster in getting responses back. Smaller standard deviation can be interpreted as there are smaller differences among each measure.*

## Discussion

Aluminum rod was a great choice as an excitation rod, but need for better the experimental settings to reduce the standard deviation of the successive velocity measurement at the same position is critical. To make the experiment more feasible to clinical environment, determining if the physical activities that stretches the tendon (ex. walking) affects the repeatability of the measurement is also needed. Since the new experimental setup has been built, developing the boundary conditions of the experimental setup to improve the precision of the data and creating a robust protocol for the average consumer are needed.

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